Initial liquid metal magnetohydrodynamic thin film flow experiments in the MeGA-loop facility at UCLA

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Abstract

Free surface, thin film flows of liquid metal were investigated experimentally in the presence of a coplanar magnetic field. This investigation was performed in a new magnetohydrodynamic (MHD) flow facility, the MeGA-loop, utilizing a low melting temperature lead–bismuth alloy as the working metal. Owing to the relatively low magnetic field produced by the present field coil system, the ordinary hydrodynamic and low MHD interaction regimes only were investigated. At the high flow speeds necessary for self cooling, the importance of a well designed and constructed channel becomes obvious. MHD drag, increasing the film height, is observed as $Ha\beta^2$ becomes greater than unity. Partial MHD laminarization of the turbulent film flows is observed when $Ha\beta/Re > 0.002$, but fully laminar flow was not reached. Suggestions for facility upgrades to achieve greater MHD interaction are presented in the context of these initial results.

1. Introduction

The use of a thin film of flowing liquid metal (LM) for the protection of a fusion reactor divertor surface has been proposed to eliminate the erosion damage and thermal stresses plaguing current high heat flux component designs. The LM film protection idea, however, is in need of further study before concerns about magnetohydrodynamic (MHD) interaction, unacceptable plasma contamination, destructive plasma wind (this topic is discussed in Ref. [1]) and adequate He pumping can be allayed. In order to deal with this first issue, several theoretical models attempting to describe the behavior of an LM film in strong magnetic fields have

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been developed [2–4]. All these models depend on the assumption of a Hartmann distribution of velocity along the toroidal magnetic field, oriented perpendicular to the main flow but in the same plane as the thin LM film (coplanar) for most designs. In order to check this assumption, a fully developed two-dimensional cross-sectional model of film flow (FDFF) was developed so that behavior of the film along the field could be determined. A discussion of FDFF as well as a comprehensive review of the LM film flow divertor ideas can be found in Ref. [5].

The purpose of the film flow experiment was twofold: to take quantitative data that validate (or discredit) the mathematical models discussed above, and to gain information about the effect of component design and general flow behavior related to LM film flows with a

free surface. This experimental effort utilized an LM flow loop–magnetic field system at UCLA, the MeGA-loop, and a thin film flow test section, FFX-1. The experimental facility and test section are described in Section 2, followed by a presentation of initial experimental results and interpretation in Section 3. A summary of significant conclusions and ideas for future work make up Section 4.

2. Experimental set-up

The MeGA-loop is a coupled LM flow loop and magnetic field facility for performing various LM experiments in a large test volume under the influence of a magnetic field. This field is generated by a set of four solenoidal magnetic field coils. At 1560 A, the resulting maximum field on axis is about 0.18 T. Field calculations show the actual field may deviate up to 5% of the average value over the test section area. The working metal is a quintary 44.7% Bi, 22.6% Pb, 19.1% In, 8.3% Sn, 5.3% Cd eutectic with a relatively low melting point. It is circulated by a variably controlled, annular, electromagnetic induction pump. Table 1 lists the characteristics of the MeGA-loop facility. A more detailed description of each system is provided in Ref. [5].

A perspective view of the FFX-1 test section is shown in Fig. 1. The test section consists of the box film former, slot nozzle, channel, table and drain pan. The box former is a stainless steel (SS) box filled with LM from the back, with a narrow slit in the front to release a film of LM. Connected to the box former is the SS slot nozzle, basically a wide rectangular duct attached to the former box that forms and stabilizes the film before it enters the channel. At the end of the slot nozzle is a gate that allows adjustment of the inlet height from 2 to 10 mm.

The free surface LM flow emerges from the slot nozzle into the channel section where the actual measurements occur. The channel is made out of an electri-

Table 1
MeGA-loop system parameters

Maximum field B (T)	0.18
Axial length (m)	0.7
Inner diameter (m)	0.8
Maximum, minimum flow rate (s^{-1})	0.5, 0.05
Loop volume (l)	15
Operating temperature (°C)	60
LM properties	
Density ρ (kg m^{-3})	9160
Melting point (°C)	47
Viscosity v (m^2 s^{-1})	1.9×10^{-7}
Electrical conductivity σ (Ω^{-1} m^{-1})	1.1×10^6

cally non-conducting, resin–fabric composite and is lined with a thin copper sheet (0.9 mm) in contact with the LM. The liner is initially wetted with the eutectic by an organic acid cleaning flux. Before the start of all test runs the LM is run through the channel at 80 °C for at least 1 h to remove any small oxide layer that may have built up. The liner's high conductivity promotes more interaction between the film and field than insulating walls. The entire former and channel is mounted on an aluminum plate that can be tilted with respect to the direction of gravity.

Measurement of the film height is accomplished with modified micrometers constructed of 300 series, non-magnetic stainless steel with measurement graduations of 0.00254 cm (1/1000 inch). Interpolation between graduations gives a factor of 10 finer resolution. A needle-like LM contact wire is attached to the micrometers and pre-wetted with Bi–Pb so that good electrical contact is insured. The micrometers are spaced every 7 cm from the gate inlet position. When the needle is lowered into the LM, the electrical potential between the needle and the channel liner is sensed with a standard multimeter, and the formation of a wake behind the contact point can be observed on the film surface.

3. Experimental results

The low magnetic field strength of the present coil system limits the investigation to flow regimes where MHD forces do not dominate viscous and inertial forces. Fig. 2 shows our proposal of the important magnetic parameters for films and the relative parameter spaces attainable by MeGA in relation to ITER. (The values marking different levels of MHD interac-
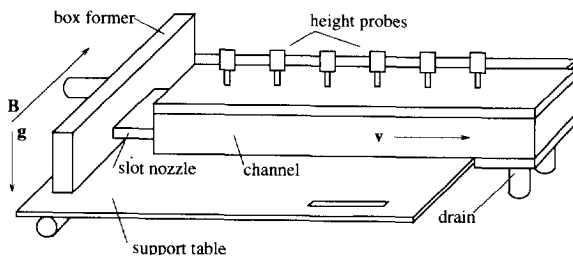

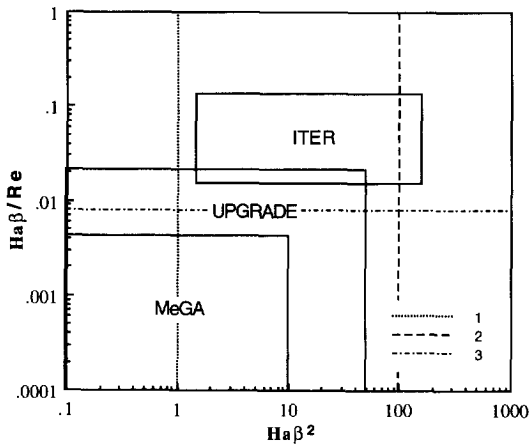Fig. 1. Perspective view of the FFX-1 test section.

Fig. 2. Magnetic parameter space of MeGA, the MeGA UP-GRADE and ITER: (1) departure from OHD, (2) formation of inviscid core flow, (3) transition to fully laminarized flow.

Fig. 3. OHD, fully turbulent film experimental data and model predictions for $Q = 0.221\,\mathrm{s}^{-1}$ and $\theta = 5°$ (Re = 13 500).

tion are themselves determined from computational results [5]. Their validation is one objective of FFX-1.) From Fig. 2 we note that while laminar flow is expected in ITER, not all reactor relevant film flows will be fully inviscid core flow. We can examine this relevant and interesting region in which interaction begins to occur and attempt to understand it further.

3.1. Zero field cases

The experiment was initially run in the absence of the magnetic field. For fully turbulent flows (Reynolds number greater than 12 500), the ordinary hydrodynamic (OHD) gradually varied flow equation using Manning's formula for channel friction [6] predicts with fair accuracy the flow height profile $h(x)$ and the normal flow height (or fully developed film height) h_n towards which the flow tends (Appendix A)

$$\frac{dh}{dx} = \frac{h^3 \sin \theta - Q^2 n^2/a^2 h^{1/3}}{h^3 \cos \theta - \gamma Q^2/a^2 g} \tag{1}$$

Fig. 3 shows a typical fully turbulent flow plotted along with Eq. (1) predictions. For the FFX channel the best values for Manning's n and γ are around 0.011 and 1.05 respectively, which are in the middle of the ranges expected for smooth metal channels [6]. Also seen in Fig. 3, the value of the height predicted for laminar flow with the same parameters is significantly below that for turbulent flow. All the MHD film models referenced in Section 1 assume that the flow field is laminar.
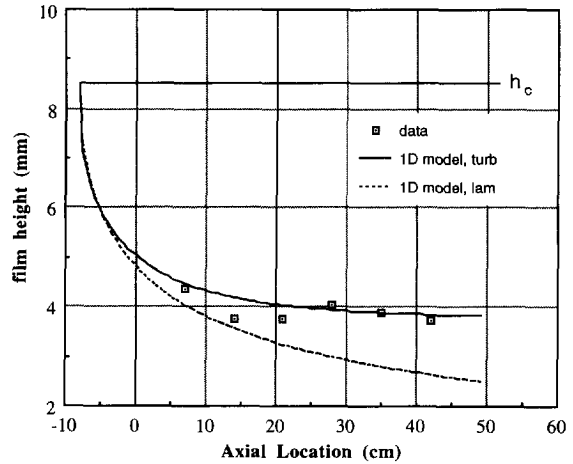
For the range of flow rates, inclination angles and initial heights investigated, the flows are almost exclusively supercritical (classified with the open-channel hydraulic terminology as types S2 and S3 flow). This type of flow is desirable for fusion because the normal flow height is an attracting one. Therefore the height of the LM film will not change significantly as the developing film approaches h_n.

For supercritical flows, capillary waves and upstream disturbances can significantly affect the downstream behavior of the film. We see in many experimental runs the importance of a properly designed film former. A rough gate rips up the surface of the LM and slight misalignment of the slot nozzle with the channel produces significant wakes that can last the entire length of the channel. Both effects increase in severity with increasing flow rate. The wakes in particular lead to difficulty in measuring the precise location of the free surface, more so than the capillary waves. The suppression of surface disturbances by a strong magnetic field has been shown in other experiments [7] and predicted by stability analysis incorporating magnetic field effects [8]. It is possible that in the strong fields of fusion reactors the formation of wakes and waves is not a critical issue. However, care should be taken with the design and manufacture of film formers for any supercritical film experiments. As is expected, the transition to subcritical flow regimes triggers the disappearance of these surface disturbances.

Attempts to set the inlet height at a calculated value of h_n can result in a flow that does not behave according to Eq. (1). Instead of a constant height profile

along the entire length of the channel, the film height dips as a result of converging streamlines under the gate (a violation of the gradually varied flow assumption), and only then recovers toward the predicted value of h_n. Attempts to launch constant height flow while avoiding converging streamlines can exhibit an initial thickness increase for wetted gate surfaces, or a depression similar to that described for non-wetted gates. We note that the developing length of super-critical films launched at an initial height greater than h_n (S2) is much shorter than that of films launched below h_n (S3). It seems better, then, to use a wetted or slightly wetted gate to launch films slightly above h_n.

3.2. Full magnetic field

On application of the field it is apparent that $Ha\beta^2$, and not the usual Ha, is indeed the important parameter indicating the magnitude of MHD drag. Even at Ha > 200 we still do not notice the dramatic MHD effects predicted for aspect ratios near unity. This is expected in duct flows as well as free surface flows owing to the elongation along the field.

The value of $Ha\beta^2$ at which we expect to begin observing an effect on the film was predicted from computational results [5] to be $Ha\beta^2 \approx 1$, with the full inviscid core region forming at $Ha\beta^2 \approx 100$. FFX-1 was unable to reach the $Ha\beta^2 = 100$ threshold but it did reach $Ha\beta^2 > 1$. Fig. 4 shows a flow with a relatively high value of $Ha\beta^2$ (and low value of $Ha\beta/Re$, this is discussed in the following paragraphs). The presence of

the full magnetic field is seen here to slow the film and thus increase the film height.

Shown also in Fig. 4 is the Eq. (1) prediction for the zero magnetic field case. This flow is still turbulent, so FDFF is not able to predict h_n. As a substitute for this, the percent increase in h_n from zero field to Ha = 200 is determined by FDFF for a purely laminar case. This percentage increase in height (drag) is applied to the turbulent OHD normal film height $h_{n,0}$ to give an estimate of the turbulent normal film height with the applied field $h_{n,200}$. Both these lines are shown in Fig. 4 and seem to be validated by the experimental data. Although this is by no means a firm validation of FDFF, it is evident as $Ha\beta^2$ passes unity that MHD drag is observed and that the magnitude of the drag predicted by FDFF gives a correct estimate of the modified h_n.

A quick mention is given here of the scatter in the experimental data. Although the micrometers are capable of very accurate measurement, the presence of large wakes on the surface at this high flow rate results in non-uniform distribution of flow across the channel which is difficult to measure. However, the average value of data seems to correspond well with model predictions. Some mollification of the disturbances can even be inferred from Fig. 4 when the field is applied. If this is truly the case, it was not noticeable on visual observation of the films.

The laminarization of LM flows is also affected by the presence of a magnetic field. This laminarization is dependent on the parameter $Ha\beta/Re$, with full laminarization as determined by Branover [9] occurring at $Ha\beta/Re > 7.7 \times 10^{-3}$ for flows elongated along the magnetic field. Branover describes the suppression of turbulence as a gradual process so that even before this critical value of $Ha\beta/Re$ an effect might be observed. Branover's estimate is a result of closed duct flow experiments and theory, and its application to free surface flows has not, to our knowledge, been verified.

For low flow rates in FFX, and thus low Re, laminarization of the film by the magnetic field is indeed observed. This laminarization is characterized by a reduction in the normal film height due to the reduced viscous drag on a laminar film as opposed to turbulent flow. Looking only at low flow rates, the average film height will be small and thus $Ha\beta^2$ less than unity. In these cases the effect of laminarization can be observed while practically no MHD drag is present. Also, the reduced flow rates result in more stable film surfaces which can be measured accurately. Fig. 5 shows just such a case where the increasing magnetic field reduces the normal film height of a low flow rate flow. Full
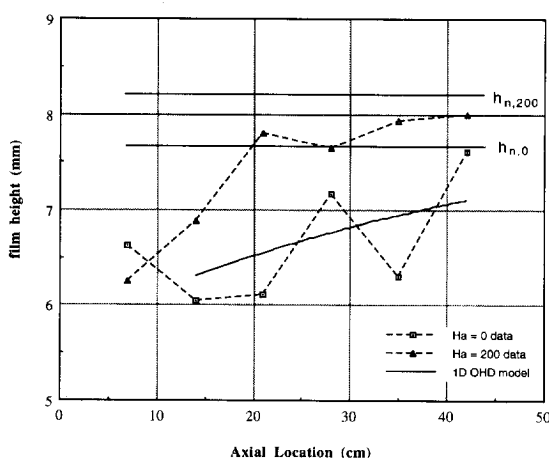

Fig. 4. MHD drag on thin film flow, $Ha\beta^2 = 5.6$, $Q = 0.33\,1\,s^{-1}$ and $\theta = 1°$ (Re = 20 300, Ha = 200, $\bar{\beta} = 0.167$).
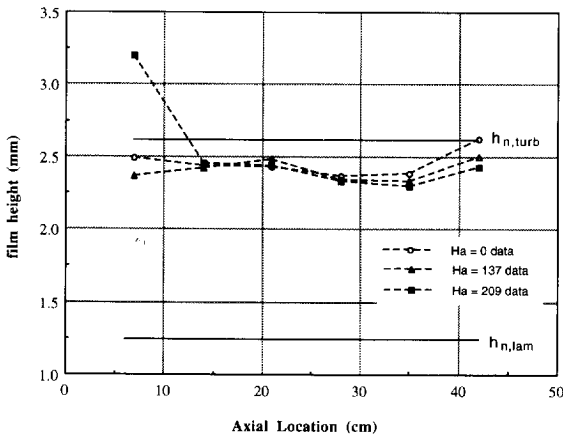
Fig. 5. MHD laminarization of thin film flow, $Q = 0.055 \, 1 \, s^{-1}$ and $\theta = 1^\circ$ (Re = 3200, $\bar{\beta} = 0.053$).

laminarization, where the film height should approach that predicted by laminar FDFF model, could not be reached. Generally, though, an effect is noticed when $Ha\beta/Re > 2 \times 10^{-3}$. Since the beginning of laminarization is observed, we conclude that the Branover limit is at least generally applicable, if not fully so, for flowing films as well as duct flows.

The effect of the MHD drag and laminarization oppose each other in their influence on the film height. Cases where both $Ha\beta^2$ and $Ha\beta/Re$ are appreciable have been avoided here so that the individual phenomena could be distinguished.

4. Summary

For clarity, the data interpretation in the preceding paragraphs can be summarized as follows.
(1) The simple gradually varied flow equation predicts fairly accurately the behavior of wide turbulent films in regions where film former disturbances are small.
(2) For supercritical flows, upstream disturbances can affect significantly the film height and surface quality, worsening as the flow rate and angle of inclination are increased.
(3) The parameter $Ha\beta^2$ and not Ha is the relevant parameter determining the relative magnitude of magnetic to viscous drag forces.
(4) At $Ha\beta^2 > 1$ magnetic drag, characterized by an increase in the film height, is seen. This experimentally measured critical $Ha\beta^2$ is a confirmation of computational predictions of [5].

(5) At $Ha\beta/Re > 2 \times 10^{-3}$ laminarization of the film, manifested as a reduction in film height, can be observed. This supports the assertion of Branover's value of 7.7×10^{-3} as the critical value of $Ha\beta/Re$ for full laminarization.

To investigate MHD interaction, modification of the MeGA facility to reach greater values of $Ha\beta^2$ and $Ha\beta/Re$ will be required. Estimates of the magnetic parameters for the MeGA UPGRADE are provided in Fig. 2, showing a five-fold increase in field obtained through the addition of an iron yoke. Estimates of the field strength put the UPGRADE field at approximately 0.85 T for a 20 cm gap. Further gains could be obtained by a change of working metals. A pure gallium or gallium–indium–tin eutectic would increase $Ha\beta^2$ by a factor of two and $Ha\beta/Re$ by three, resulting in a parameter capability well into the ITER relevant range.

Acknowledgements

Appendix A: Nomenclature

$h_{n,c}$	normal and critical film heights
n	Manning's turbulence coefficient
γ	kinetic energy correction factor
ρ, ν, σ	density, viscosity and electrical conductivity
a, θ	channel width and angle of inclination
B, Q	magnetic induction and volume flow rate
Ha	Hartmann number, $Ha = B(a/2)(\sigma/\nu\rho)^{1/2}$
Re	Reynolds number, $Re = Q/a\nu$
β	aspect ratio, $\beta = h/(a/2)$

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